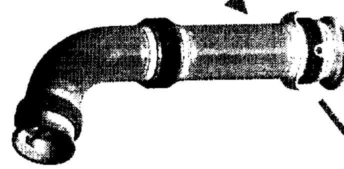
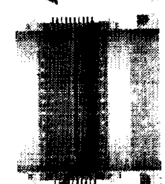




Space Shuttle Fuel Feedliner Cracking Investigation
*MSFC Fluids Workshop*
November 19-21, 2002

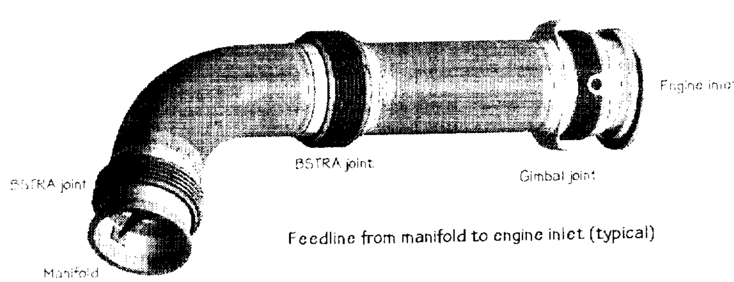
TD63/Tom Nesman

Space Shuttle Program



## Introduction

- Cracks found on all orbiters fuel feedline bellows liner → fleet grounded
  - Near cleaning slots in liner
  - Cracks from 0.1" to 0.3" in length OV103, OV104, & OV105
  - Slot-to-slot cracks OV102
- JSC → Three management teams
  - Representatives from MSFC
- Seven technical teams reporting to one of management teams
  - Participants from NASA (JSC, KSC & MSFC), Boeing, USA, & Arrowhead




Feedline from manifold to engine inlet (typical)

## Significant Activities

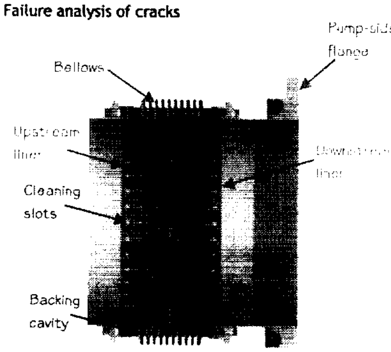
*to Pursue for Next (and subs) Flight*

**Significant Findings**

- 3 different ducts on orbiter (Eng1, Eng2, Eng3)
- Lox & LH2 ducts are identical
- Orbiter duct cracks specific to LH2 duct*
- Cracks only in bellows liner closest to engine
- Cracks all originate at a liner slot
- Slots are stamped (leaving vertical indications)
- Cracks found after initial lox duct qual test series (attributed to over-test)
- After initial qual, liner redesigned & requalified
  - Liner material: CRES 321 to INCO 718
  - Number of slots: 76 slots to 38 slots
- OV102 & MPTA old design ... others new design
- Flight-type ducts not used on SSME single engine tests
- Reassed flight data & analyses says qual OK bellow 1000 Hz
- Analyzed material is OK without significant manufacturing defects (spare liners)
- Installation test showed no damaging strains
- By analysis
  - Pump excitations can excite liner modes with high stresses at all crack locations

**Repair and Flight Qualification Work**

- Repair method validated with coupon tests
- Orbiter liners repaired → weld cracks, grind and smooth
- Testing → single engine hotfire data 4" upstream of LPFP flange
- Modal tests of liners (air and water)
- Refined load analyses (vibrations, acoustics, flow)
- Failure analysis of cracks




** Only Eng 1 and Eng 2 found to have flowliner cracks*





## Elements of Cracking Analysis

| | | | |
|---|---|---|---|
| 1. | Failure Analysis | → | LCF, HCF, overstress |
| 2. | Material Capability | → | Material properties in $LH_2$ at T and P |
| 3. | Loads | → | Static, dynamic, transient, flow, vibrations |
| 4. | Structural Model | → | Natural $f$'s, mode shapes, stress, FSI, coupling |

The evaluation of cracking mechanisms is accomplished through the four analysis elements listed above. To be credible, a postulated mechanism must have sufficient definition in terms of each of these elements. In most cases a conservative estimate with a significant variance is traded versus the investment in obtaining a detailed definition.

## Fluid Driven Cracking Analysis

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- Crack initiation and growth requires a driving mechanism or load
- HCF cracks at regular repeatable locations (pattern) could be caused by a driving mechanism that is coincident with a structural mode (resonance)
- There are three parts to investigating potential fluid driven cracking
  1. Compare potential load mechanisms to structural modes
     - Forced response ... periodic load and structure mode frequencies are not coincident
     - Random excitation ... structural mode excited by random amplitude forces
     - Resonance ... periodic load is coincident with structural mode frequency
  2. Determine changes in frequency of load and structure during launch vehicle ascent
     - Frequency coincidence may only occur during throttling
     - Frequencies may coincide for limited parts of main stage
     - Frequencies may coincide for duration of main stage
     - Frequency coincidence may occur differently on each engine / vehicle combination
  3. Determine load and response patterns (spatial variation)
     - Structural mode should have highest stresses at crack location
     - Dynamic load should put energy into structural vibration
     - Structural "lock-in" should be considered



## Coordinated Effort

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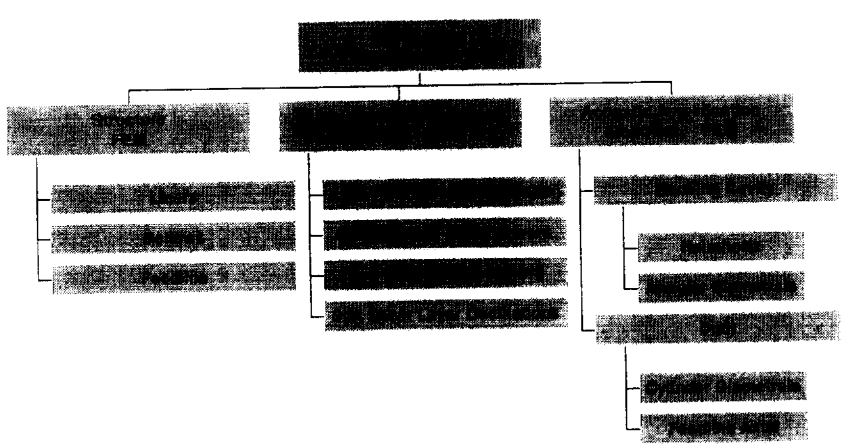

## Liner Structural Modes

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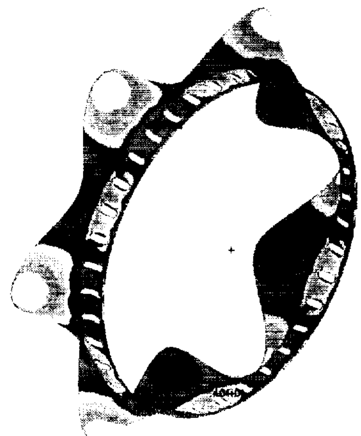
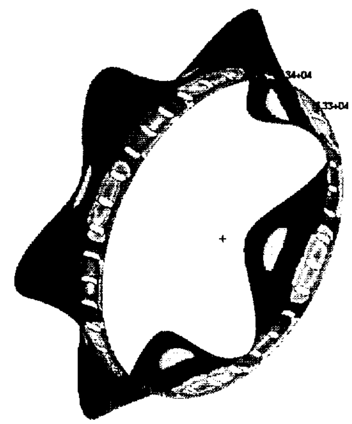
- The lowest frequency mode of the downstream flowliner is the 6th diametral shown bellow
- This is because midway from the welded end the cantilevered cylindrical shell transitions to a smaller diameter
- The 6th diametral mode puts high stresses at all of the crack locations



**Hoop Dynamic Stress**



**Axial Dynamic Stress**

*FEM by ED21/ Frady*



## Bellows Structural Modes

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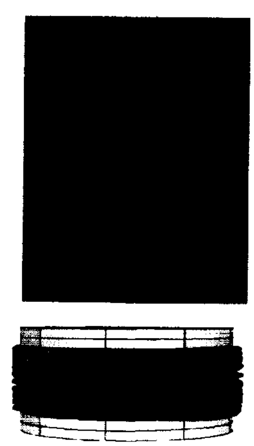

*FEM by ED21/ Frady*

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## Structural Motion in a Fluid

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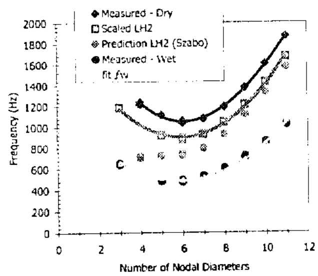
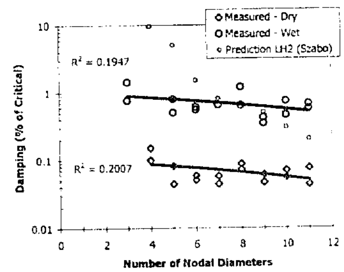
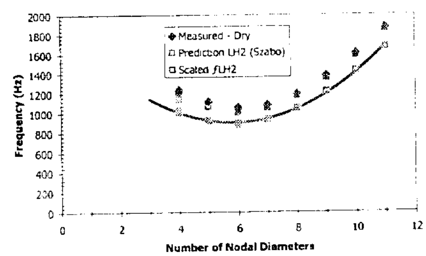



- Structural motion in liquid hydrogen will be reduced in frequency and magnitude compared to air
- The retarded motion is modeled using an added mass and an increased damping
- For the downstream fuel feedliner the frequency (above left) and damping (above right) change in water was predicted, then measured
- The same model was used to predict the frequency change due to LH2 (right) and compared to water data scaled to LH2






Fluid Physics & Dynamics

## Fluid Borne Drivers

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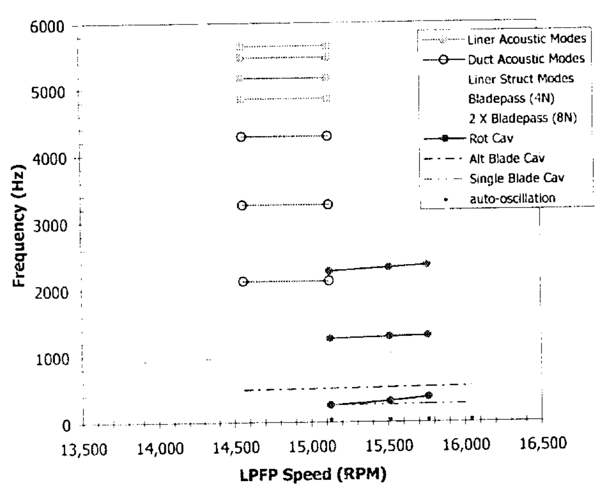
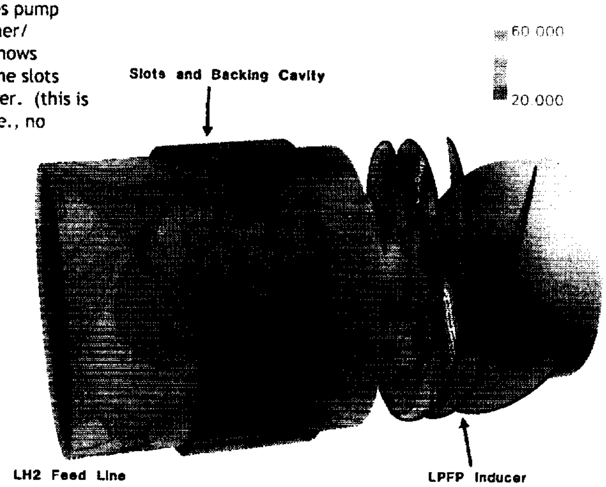


3D CFD (TD64/Dorney) provides pump backflow in line and also in Liner/ Bellows backing cavity. This shows amount of flow in and out of the slots and also the ΔP load on the liner. (this is a single phase flow analysis, i.e., no cavitation)



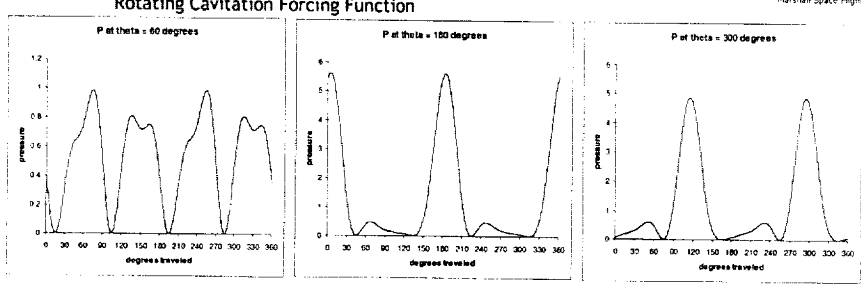

**Instantaneous Static Pressure**

*3D CFD by TD64/ Dorney*



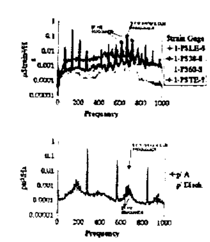


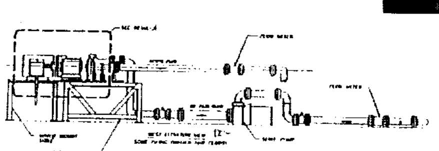
Rotating Cavitation Forcing Function




*Waveforms modeled by TD63/ Zoladz & Mulder*

Fluid Physics and Dynamics Group (T. Zoladz)
- Builds on MSFC cold flow legacy
- Cavitation flow loads proved in water flow
  - Mapped pump cavitation regimes
  - 3 wave theory
- Predicted wave forms for flowliner loading above
- Wave forms calibrated using single engine data



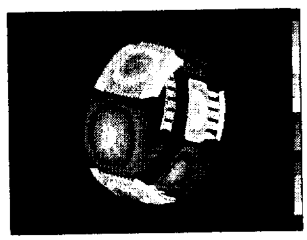



## Amplification Mechanisms

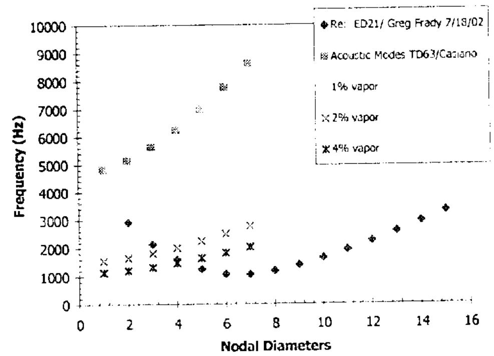


### Acoustic Modes Between Liner and Bellows

Third Tangential Mode (3T)



### Effect of Cavitation on Acoustic Modes



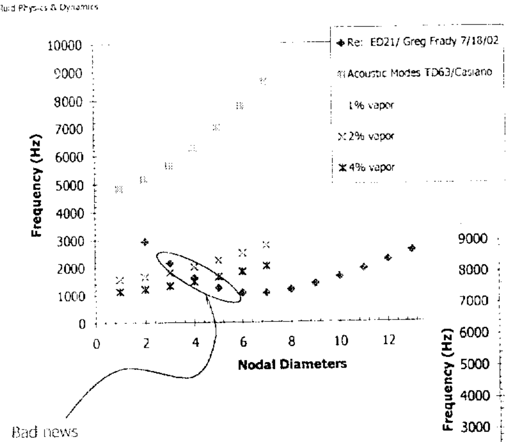

*Fluid FEM by TD63/ Casiano*

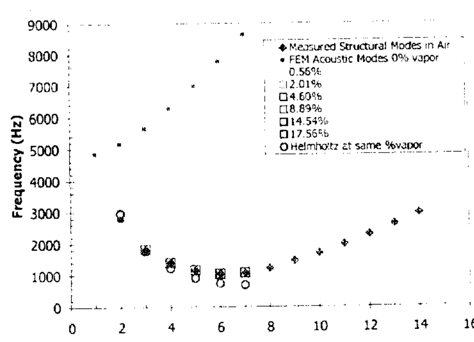




## Effect of Vapor on Acoustic Modes





## Flow Parameter Mapping

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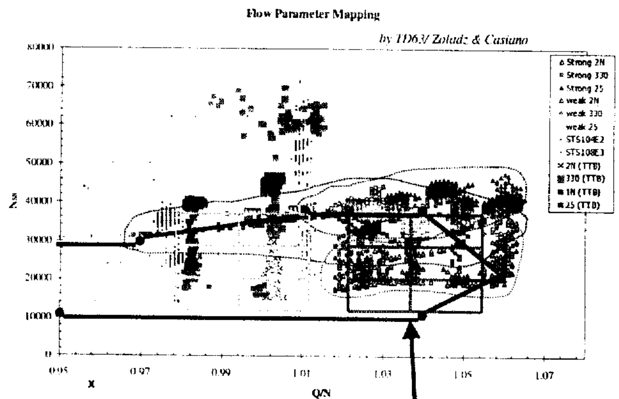


OV104 BII and BIIA (from TD61)

- Data include
  - Test 902-812
  - Test 902-813
  - Test 902-818
  - Test 902-819
  - Test 902-824
  - Test 902-827
  - TTB Test 47
  - TTB Test 49
  - TTB Test 64
  - STS104 Block II engine
  - STS108 Block II engine
- Notes:
  - For all data, Q/N, and Nss are based off of LPFP inlet conditions
  - TTB data mapping
    - 25Hz, 1N, 330 Hz, and 2N **presence** based off of LPFP outlet measurements
  - Test 902 data mapping
    - 330Hz and 2N **levels** based off of pump and turbine accels
    - 25 Hz **levels** based off of balance cavity pressure measurement

<u>Mapping level characterization</u>

No response < 1.2 RMS
Weak response ≥ 1.2 RMS
Strong response > 1.6 RMS

- Cavitation phenomena observed in SSME data
  - 2N: alternating blade cavitation
  - 330 Hz: rotating cavitation
  - 25 Hz: auto-oscillation

- Characterized and mapped the 25 Hz response
- Cavitation instabilities have shown to map well with cavitation and incidence parameters



## Flight Engine Flow Map

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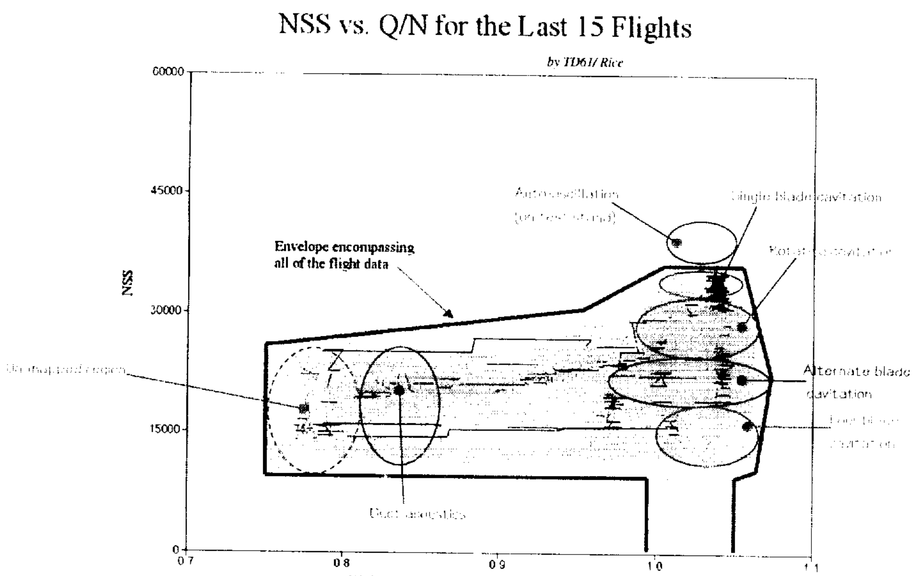

## Summary / Conclusion

- Flow loads investigated as possible driver for cracks found in orbiter fuel feedliner
- Analysis shows that pump excitations can excite liner modes with high stresses at all crack locations
- Three aspects of fluid driven cracking were investigated and it was found that
  1. Pump blade pass frequency is the only driving mechanisms that coincides with liner structural frequencies
  2. The time and duration of frequency coincidence is not known due to changes in frequency of load during launch vehicle ascent and uncertainty in exact structural mode involved
  3. The lobed pattern from pump pulsations are most likely to excite a nodal diameter mode of the liner

- Ongoing testing should reveal information to improve hardware life estimates
  - Liner response mode (or modes)
  - Accuracy of liner delta p' estimate
  - Spatial p' mapping